View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Activos Digitales IAPH

Journal of Coastal Research	SI 48	55-63	III SCCG (Proceedings)	Spain	ISSN 0749-0208

Historical evolution and present state of the coastal dune systems in the Atlantic coast of Cádiz (SW Spain): Palaeoclimatic and environmental implications

J. Gracia†, L. Del Río†, C. Alonso‡, J. Benavente† and G. Anfuso†

†Dpto. Geología, Facultad de Ciencias del Mar y Ambientales. Universidad de Cádiz. 11510 Puerto Real, Spain. e-mail: javier.gracia@uca.es

‡Instituto Andaluz del Patrimonio Histórico. Consejería de Cultura, Junta de Andalucía. Avda. Duque de Nájera, 3. 11002 Cádiz, Spain. e-mail: cayac@arrakis.es

ABSTRACT

GRACIA, J.; DEL RIO, L.; ALONSO, C.; BENAVENTE, J. and ANFUSO, G., 2006. Historical evolution and present state of coastal dune systems in the Atlantic coast of Cádiz (SW Spain): Palaeoclimatic and environmental implications. *Journal of Coastal Research*, SI 48 (Proceedings of the 3rd Spanish Conference on Coastal Geomorphology), 55-63. Las Palmas de Gran Canaria – Spain, ISSN 0749-0208

This paper examines the origin, evolution and present state of the coastal dunes along the South Atlantic Spanish coast from the Guadalquivir River mouth to the Strait of Gibraltar. Wind regime in the zone is strongly affected by the North Atlantic Oscillation (NAO). Low or negative NAO index values give rise to the prevalence of westerly humid winds, while during periods with a positive NAO index easterly, dry winds prevail. Several Holocene and historical aeolian phases have been identified in the zone, represented by different aeolian deposits, many of them containing archaeological remains. The oldest one dates to shortly after the mid-Holocene eustatic maximum. During historical times dune-building episodes were associated with a higher frequency and persistence of easterly winds. During the 20th century, and especially in the last few decades, the prevalence of positive values of the NAO index has favored the growth and advance of mobile dunes in the vicinity of the Strait of Gibraltar. In contrast, dune ridges associated with westerly winds are much less mobile or stable and form shore-parallel ridges covered by vegetation.

ADITIONAL INDEX WORDS: *Holocene, NAO, climatic change, environmental impact, coastal management*

INTRODUCTION

This paper deals with the origin, historical evolution and present state of the coastal dunes along the South Atlantic Spanish coast, from the Guadalquivir River mouth to the Strait of Gibraltar. The formation of coastal dunes is related to several key factors that control their occurrence, development and importance. These can be grouped into three categories: geomorphological setting (coastal orientation, tidal range, wave energy, beach profile behaviour); sediment supply; and climate (direction and intensity of winds, rainfall, etc.). As a consequence, major coastal dune fields generally develop on moderate-high energy coasts of temperate regions where dominant winds blow from the west, on coasts subject to east-facing swell waves (JENNINGS, 1964). Hence, the Atlantic coast of Cádiz Province meets the requirements for well-developed dune systems.

The coast of Cádiz is a mesotidal environment with low-energy waves (BENAVENTE *et al.*, 2002), which accounts for the dissipative-intermediate state of most beaches in this area. However, these conditions progressively change towards the Strait of Gibraltar, where the coast is microtidal and the prevailing beaches are in the intermediate-reflective domain. These dynamic factors mean that shore-parallel dune ridges related to westerly winds occur mainly in the northern part of the study area. From Cape Trafalgar southwards (Fig. 1), these kinds of dune systems are much less frequent., Easterly winds, blowing from the Strait of Gibraltar prevail in the southern zone.

Another important factor in dune development is coastal configuration. Straight NW-SE coastal sectors of the Cádiz coast are broadly perpendicular to westerly winds, so dune ridges are typically shore-parallel. On the other hand, Plio-Quaternary tectonics created a series of small embayments oriented southwards and facing easterly winds.

A considerable sedimentary supply is usually required for the formation of dune systems, and this sediment is a surplus from nearby beaches (BIRD AND JONES, 1988). Dune development is thus generally higher near important river mouths, as in the northern part of the study area that is close to Guadalquivir and Guadalete river mouths. Both rivers used to deliver a large amount of sediments to the coast, which accumulated on the beaches and dune fields. However, sediment supply from river basins in the province of Cádiz has been significantly reduced in the 20th century due to intense river regulation (dams, channelization, etc.).

CLIMATIC BACKGROUND

The study area has a Mediterranean climate, yet being located in the Atlantic coast of the Iberian Peninsula entails higher air humidity, higher rainfall and milder maximum and minimum temperatures throughout the year. The dry and warm season is

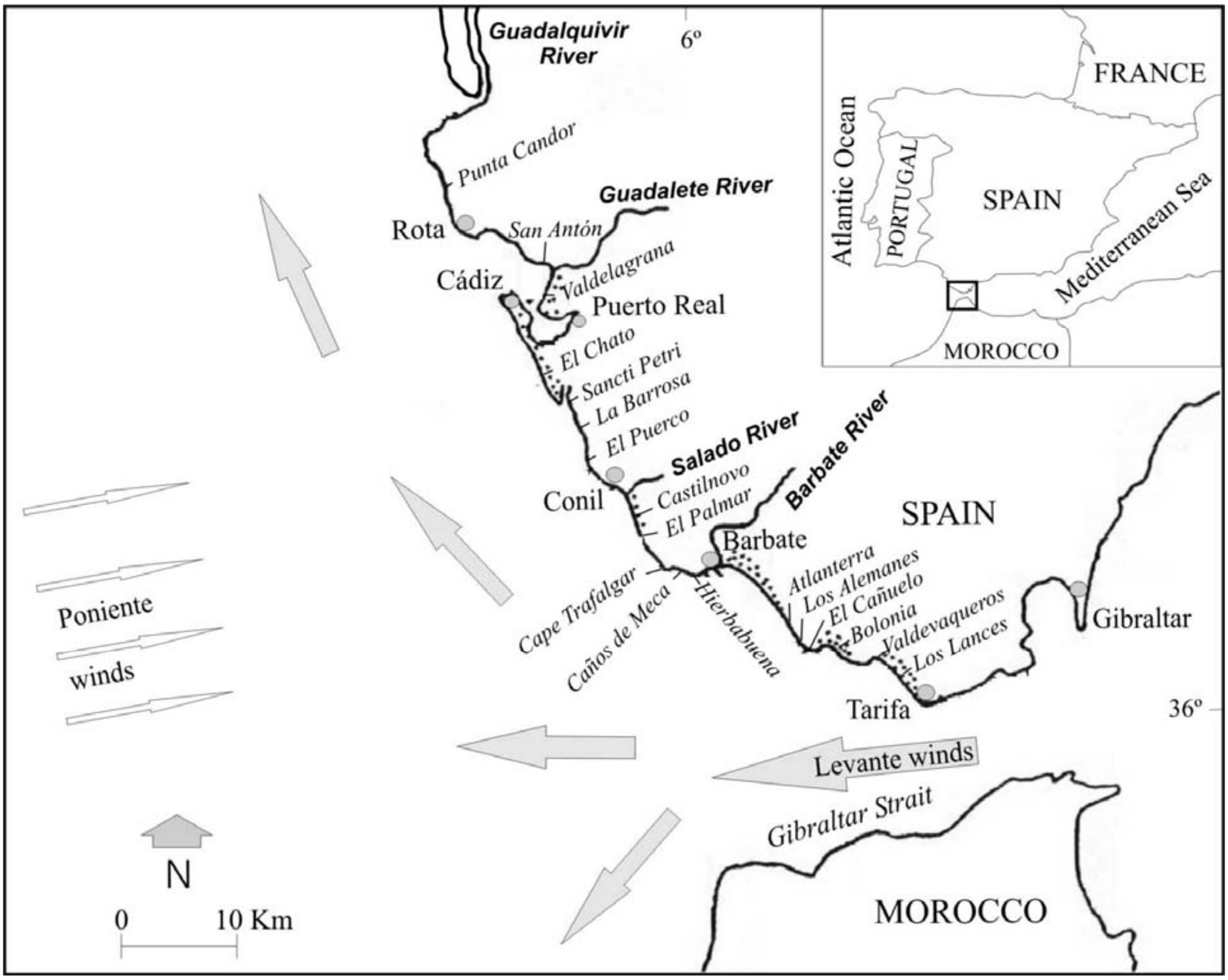

Figure 1. Location map of the study zone, with prevailing wind directions and location of main dune systems cited in the text.

typically longer than the wet and cool season. Average annual rainfall is around 600 mm/year (SÁNCHEZ, 1988) and precipitation is mainly distributed in winter months.

The summer season is characterised by warm and dry anticyclonic conditions, which derive from the strengthening and extension of the Azores High over central Europe. Dry easterly winds, called *Levante*, dominate in the Gulf of Cádiz blowing from the Mediterranean. When winds pass through the Strait of Gibraltar they are channelized and accelerated due to the Venturi effect. Once in the Gulf of Cádiz, they diverge and affect the Cádiz coast blowing from the SE (Fig. 1). These winds have an annual occurrence of 19.6% and an average wind speed of 27.8 km/h, with occasional gusts reaching 110 km/h (SÁNCHEZ, 1988). These winds play an important role in erosion and transport processes due to their high intensity.

In winter, the Azores High weakens while the Icelandic Low grows stronger. This leads to a decrease of the summer anticyclonic conditions over the Iberian Peninsula and the cyclone systems from the Atlantic can then take a more southward path and reach the southern parts of Spain. During these situations, warm, moist, westerly winds from the Atlantic Ocean prevail. They are called *Poniente* (Fig. 1) and have an occurrence of 12.8% and an average speed of 15.8 km/h (SÁNCHEZ, 1988).

These two winds account for more than 50% of total wind frequency (Fig. 2). Other significant winds in this area blow from the SW, WSW and W, although in general all these west-component winds are associated either with marine breezes or mid-Atlantic low pressure situations.

The Gulf of Cadiz climate and wind regime is strongly affected by the North Atlantic Oscillation (NAO). The difference between the sea level pressure at the Azores High and the Icelandic Low gives an index of the NAO strength (HURRELL, 1995). During years with low or negative NAO index values, pressure decreases in the subtropical area and the Azores High weakens, more cyclones from the Atlantic can invade the Iberian Peninsula and cause intense rainfall and floods. In contrast, during years when the NAO is in a positive phase (pressure rises over the Azores and drops over Iceland) there is an intensification of the high pressure in the western Iberian Peninsula and easterly winds become stronger. This blocking situation over the area, with *Levante* winds blowing continuously, can extend over the whole year.

Some recent studies indicate that, throughout the last two decades, the northern centre of the NAO (i.e., the Icelandic Low) has moved closer to Scandinavia. This shift has major implications for the precipitation and wind over the Iberian Peninsula and could be one of the reasons for the decreasing mean seasonal rainfall over the last decades (TRIGO *et al*., 2004). GOODESS AND JONES (2002) compared the NAO-winter index and the winter precipitation in the Iberian Peninsula over the last 40

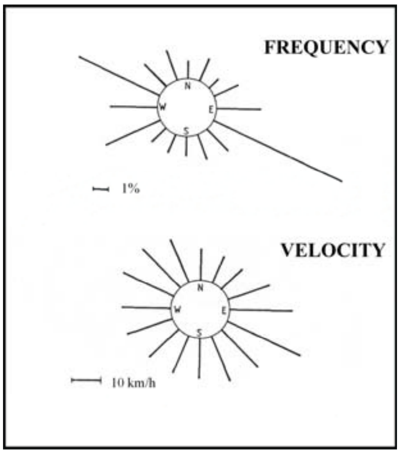

Figure 2. Wind rose displaying wind frequency and speed on the coast of Cádiz (MUÑOZ-PÉREZ AND SÁNCHEZ, 1994).

years; the results showed a significant correlation, especially for the Gulf of Cádiz and Guadalquivir River basin (ABERG, 2005).

Regarding the potential for generating dune systems, *Levante* winds would theoretically be the most important due to the low moisture content and high speed. However, in most parts of the study area *Levante* winds blow roughly shore-parallel, preventing dune ridge formation. Only the embayments developed in the southern zone allow for dune development, and these usually have very large and mobile dunes. On the other hand, *Poniente* winds blow in a shore-normal onshore direction, but they have high moisture content. As a consequence, they produce very continuous dune ridges along the backshores but with low or zero mobility.

HOLOCENE AND HISTORICAL EVOLUTION

Coastal dunes in the Gulf of Cádiz are mainly associated with beach ridges and spit barriers. During recent Holocene and historical times several periods of increased aeolian deposition took place along this coast, very probably related to climatic fluctuations and sea-level oscillations. BORJA *et al.* (1999) made a synthesis of the aeolian phases recorded along the Gulf of Cadiz and defined three main systems: D1 (2700 cal BP to 2000 cal. BP), D2 (14^{th} to 17^{th} centuries AD) and D3 (17^{th} century).

The Holocene sea-level maximum, about 2-3 m above present sea level, was reached in Southern Spain by ca. 6500 yr BP (ZAZO *et al.*, 1994). From that moment, several spit barrier systems enclosed the estuaries, while open coast beaches developed beach-ridge systems. Systematic studies carried out along the Southern Iberian coasts by ZAZO *et al.* (1994, 1996), GOY *et al.* (1996) and DABRIO *et al.* (2000) concluded four major prograding episodes, named by ZAZO *et al.* (1994) as H1 to H4 and with the following ages (cal. Ka BP; BORJA *et al.*, 1999): H1, 6.5 – 4.7; H2, 4.4 – 2.7; H3: 2.4 – 0.7 and H4, 0.5 to present. A more detailed study developed by GOY *et al.* (2003) in the Gulf of Almería (Western Mediterranean) defined six prograding units with radiocarbon ages (cal. ka BP): H1, 7.4 – 6.0; H2, 5.4 – 4.2; H3, 4.2 – 3.0; H4, 2.7 – 1.9; H5, 1.9 – 1.1 and H6, 0.5 – present. The evident discrepancies between the general scheme and the local cases suggest the need for deeper studies and additional age determinations on different Holocene coastal records along the southern Spanish coast. Nevertheless, it is evident that the oldest beach-ridge unit, H1, commenced during the maximum Holocene sea-level high on the Southern Spanish coast, after which beach deposition and coastal progradation prevailed, subject to slight sea-level fluctuations and minor climatic oscillations.

During their studies, the previously cited authors did not identify any subaerial H1 record (neither beach nor aeolian deposit) in the littoral spits of the Gulf of Cádiz. The absence of H1 deposits in the Atlantic spit systems was interpreted by GOY *et al.* (1996) and DABRIO *et al.* (2000) as a consequence of the prevalence of coastal aggradation as compared with progradation. A large part of the fluvial sediment supply would have been trapped in the central basins of estuaries during the highstand. These authors neither found any aeolian sediment between 6500 and 2500 cal. BP in the Gulf of Cádiz. Following BORJA *et al.* (1999), the absence of aeolian sediments of that age may be related to the evolution of estuaries and their limiting estuarine barriers in the area during the deposition of spit unit H1. Afterwards, during deposition of spit system H2 sedimentation would have taken place mostly in the axial zones and sediment supply increased, improving the preservation potential of the subaerial parts of the spits (DABRIO *et al.*, 1999).

Several recent studies carried out in the Bay of Cádiz (GRACIA *et al.*, 2000, 2002) show the local existence of Holocene beach and dune deposits chronologically related to early times shortly after the mid-Holocene eustatic maximum. About 3 km to the SE of Puerto Real village, inside a small coastal embayment, GRACIA *et al.* (2000) identified a marine terrace at about 3 m above mean sea level, composed of 1.5 m of coarse bioclastic sands overlain by weathered aeolian fine sands. The radiocarbon dating of the low beach deposit yielded cal. 5.3 – 4.8 ka BP - equivalent to the regional morphosedimentary unit H1 described by ZAZO *et al.* (1994), or to unit H2 if considering the Almería beach-ridge set (GOY *et al.*, 2003) as a pattern. This finding does not nullify the assumption of a prevalence of aggradational processes inside the bays and estuaries during the early post-eustatic maximum times. However, at that moment a certain amount of fluvial sediment supply was very probably transported out of the estuaries (especially during fluvial flooding episodes) and later distributed alongshore by littoral currents, forming beaches in sheltered areas.

One km to the NW of Puerto Real Hospital, at El Retamar place, an archaeological Neolithic site was found within a palaeosol level developed at the base of a 1.5 m thick aeolian sand deposit. Radiocarbon dating of seeds found in the remains of a hearth gave an age of cal. 7.2 – 6.8 ka BP (STIPP AND TIMERS, 2002). The deposit forms part of a climbing dune that covers the southern gentle slope of a low hill, reaching a height of about 20 m a.m.s.l. Sediment supply to the dune is represented by a sandy palaeobeach that extends all along a coastal plain ("Manchón de Mora"), at about 4 m a.m.s.l. at present partially covered by vegetation (Fig. 3). The morphology and orientation of the aeolian sand body indicates that the main winds responsible for its generation blew from the SSE. Very similar presently-active climbing dunes appear at different points of the Cadiz coast, and these are always generated by *Levante* winds. The age of El Retamar dune system is equivalent to regional spit-barrier unit H1.

BORJA *et al.* (1999) indicated that accumulation of the first aeolian system (D1) in the Gulf of Cádiz began about 2.5 ka BP, shortly after a firm emerged substratum of H2 age existed. Obviously, the climbing dune of El Retamar suggests that very probably aeolian accumulation began much earlier, although perhaps in these initial moments it was not a widespread process, but only restricted to favourable points. The Manchón de Mora palaeoembayment is located only 1 km downdrift of the historical situation of the most important river mouth in the region (Guadalete River), on a sheltered area quite favourable for the development of a pocket beach. In any case, the El Retamar dune

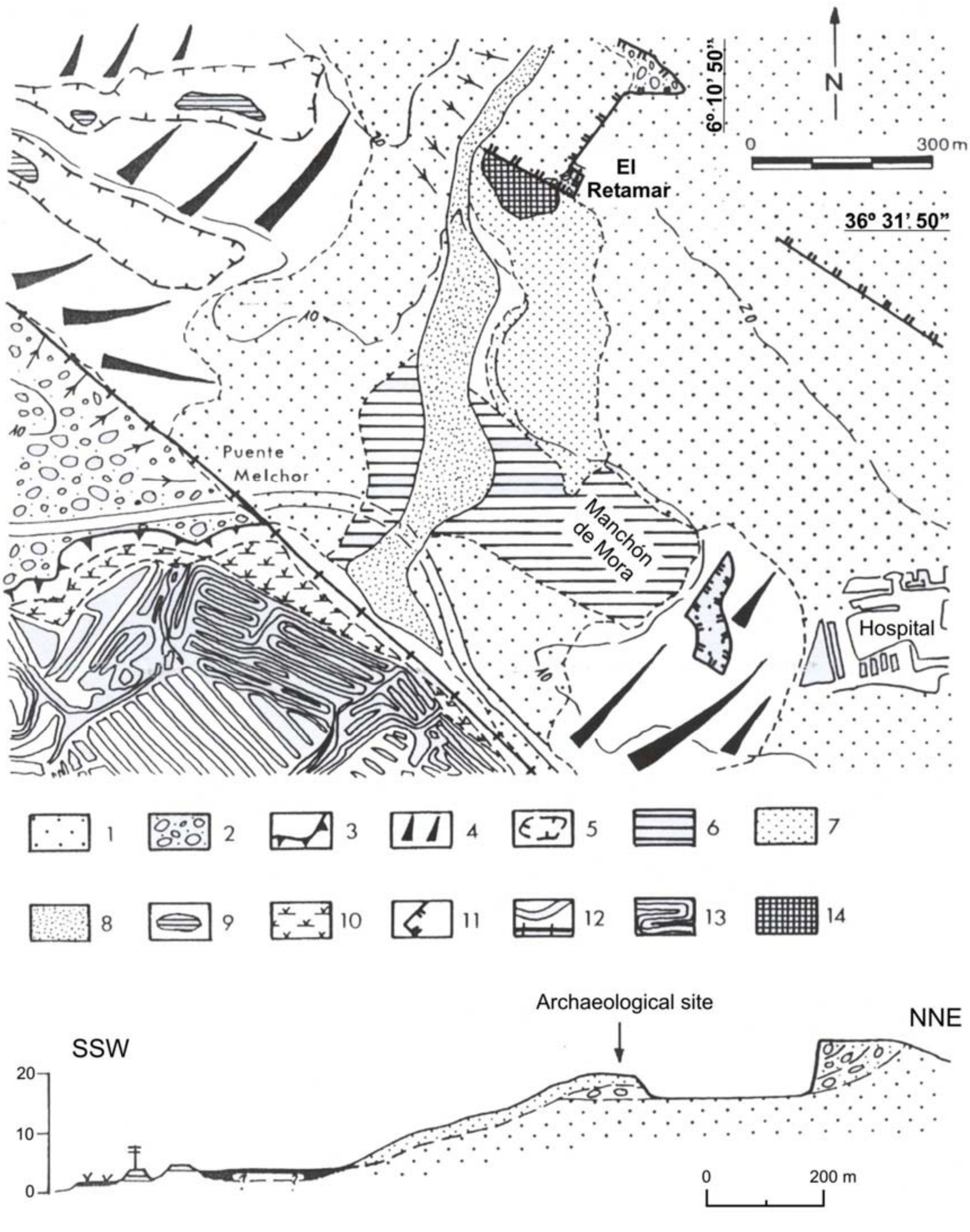

Figure 3. Geomorphological map and cross section of the El Retamar archaeological site (modified from GRACIA *et al.*, 2002). Symbols: 1, Pliocene sands; 2, Plio-Pleistocene conglomerates; 3, Structural scarpment; 4, Pleistocene pediment; 5, Closed depression, doline; 6, Coastal sedimentary plain; 7, Holocene aeolian deposit; 8, Valley bottom; 9, Ephemeral pond; 10, Vegetated salt marshes; 11, Gravel pit; 12, Roads, railway; 13, Salt ponds; 14, Archaeological site. Contour lines in m.

suggests a period during which *Levante* winds had enough intensity and persistence to build a dune that climbed 20 m.

During historical times, after the 8th century B.C. many Phoenician settlements were abandoned and covered by thick aeolian deposits. About the 5th century B.C., a slight climatic change took place in SW Spain to more humid and fresh conditions, represented by an increased fluvial sediment supply to the coast (BORJA, 1992). These climatic conditions favoured the development of organic soils upon previous aeolian deposits, which were occupied by human settlements, even in open spaces, during the whole Roman period (between 2000 to 700 cal. BP; BORJA *et al*., 1999).

Afterwards, by the late warm Medieval period, the coastal zone in SW Spain was once more affected by aeolian deposition, generated by *Levante* winds. Many Roman and Early Medieval settlements located at the western sides of the bays along the Cadiz coast (Valdevaqueros, Bolonia, Barbate, Cádiz Bay, etc.) are covered by thick aeolian deposits (ALONSO *et al*., 2004). This historical sequence of aeolian episodes related to Levante winds separated by humid periods of soil development and human settlement can be seen in several stratigraphic sections at different points along the Cádiz coast. An example of this sequence can be seen in Figure 4, a 9 m deep excavation made on a plot in Escalzo Street (Cádiz city), in a zone completely exposed to easterly winds.

This phase of aeolian deposition probably lasted until the 17th century (Borja *et al*., 1999). During the Little Ice Age (18th to 19th centuries) a prevalence of humid *Poniente* winds, an increase in rainfall and a widespread temperature decrease favoured a new phase of soil development. Finally, during the 20th century renewed dry *Levante* conditions prevailed, leading to the reactivation of mobile dunes on the Cádiz coast.

From their regional study, BORJA *et al*. (1999) concluded that historical aeolian systems began to accumulate during periods of higher sea level under long-lasting cyclonic (low-pressure, humid-temperate) conditions. However, these authors recognized that the organic palaeosol developed during the regional "Roman-medieval discontinuity" (2000 cal BP to 700 cal. BP), that is largely coeval with the spit barrier unit H3, discourages direct correlations between humidity and gaps. The numerous examples of historical association between easterly (*Levante*) warm and dry wind prevalence and reactivation of mobile dunes indicate that such a simple relationship is far from proven.

PRESENT STATE OF THE DUNE COMPLEXES

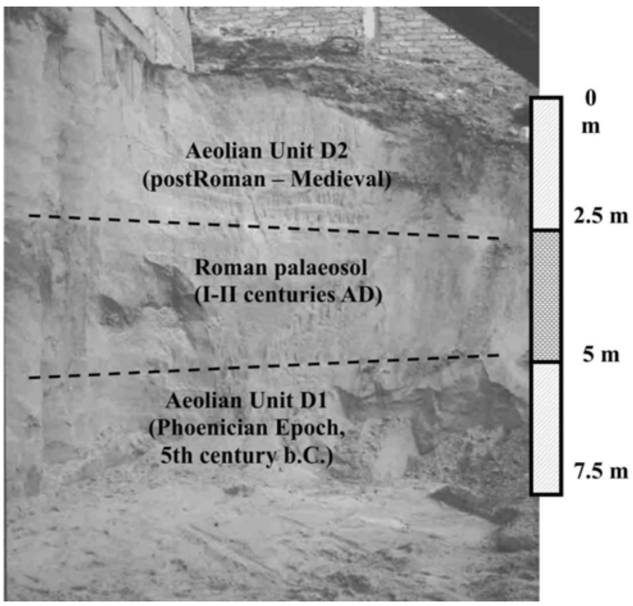

Figure 4. Stratigraphic section on Escalzo Street (Cádiz city), where different historical aeolian deposits can be identified, separated by palaeosols.

Morphological and dynamic characteristics of dunes on the Atlantic coast of Cadiz Province are clearly different in the northern and southern parts of the study area. Detailed analysis of aerial photographs from 1956 to 2002 shows that recent evolution of coastal dunes exhibits marked contrasts between the north and the south coast of the province as well.

Northern coast

The northern part of the study area, located between the mouth of Guadalquivir River and Cape Trafalgar (Fig. 1), is a mesotidal low sandy coast directly exposed to dominant westerly (*Poniente*) storm winds. Most beaches in this zone are wide and dissipative, with a marked seasonal behaviour (BENAVENTE *et al*., 2002). Important rivers like Guadalquivir and Guadalete flow into the Atlantic Ocean in this area, together with minor streams like Salado and Barbate, which supply fine-grained sediments to the coast. These conditions favor the development of dune systems (CARTER, 1988).

Shore-normal *Poniente* winds generate dune ridges parallel to the coast that show a typical sequence with embryo dunes and foredunes on the upper backshore and dunes stabilized by vegetation behind the beach, as in El Chato beach (Fig. 1). At some points along the coast, topography and sand supply have led to the development of aeolian sheets and dunes stabilized by pine trees at the back of coastal dune ridges, as in the formerly active San Antón dunes. Climbing dunes associated with low cliffs are also present at several points along the coast, such as El Puerco beach (Fig. 5).

Free barchan dunes are very rare in this coastal stretch and they only appear at the end of Sancti Petri sand spit (Fig. 1), a very dynamic area with no vegetation on the dunes due to the high exposure to strong *Levante* winds.

Dune systems in the northern study zone are threatened by intense human pressure in many places along the coast. Large areas of former dune fields and aeolian sandsheets have been destroyed by urban development in the last 50 years.

Sand mining for building purposes used to be frequent, but the main impact was the construction of buildings and promenades directly on the dunes in many places, especially during the tourism boom experienced in Spain in the 1960s and 70s. In fact, most tourism facilities on the coast of Cadiz were built during those years, including very popular resorts like Valdelagrana or La Barrosa (Fig. 1). In the former about 160,000 m^2 of dune field area were destroyed between 1956 and 2002, mostly in the 70s and early 80s.

In La Barrosa beach around 190,000 m^2 of dunes and 70% of the extensive aeolian sheet behind them have been destroyed in the last 50 years. Despite a renewed urbanization trend on this coast since the late 1990s, the Spanish Shores Act came into force in 1988, and as it forbids building on beach and dune areas, it is helping to preserve dune ridges in places like El Puerco beach, where new resorts have been built behind the dunes.

In addition to direct removal for building purposes, dune systems in this area are endangered by natural processes intensified by human action. Wave erosion and lack of sediment supply are responsible for the absence of embryo dunes in many shore-parallel dune fields, like Punta Candor and El Palmar. Here the steep seaward slope of dune ridges and the presence of plant roots on seaward dune faces are also indicative of coastal erosion. In fact, recent shoreline retreat (DOMÍNGUEZ *et al.*, 2004; DEL RÍO *et al.*, 2005) has resulted in the complete destruction of dune ridges in the last few decades in a few places along the coast, such as Punta Candor. Such erosion is mainly caused by a large reduction in sediment supply to the coast due to the extensive

Figure 5. Climbing dunes at El Puerco beach (near Conil village).

damming of Guadalquivir and Guadalete rivers since the 1950's and to a lesser extent by disruption in sediment transport due to coastal engineering structures.

The most spectacular case of shoreline retreat in this area is Valdelagrana sand spit. Here the construction and lengthening of two jetties at the mouth of Guadalete River in the late 1970s and early 80s, together with the building of dams on its basin, has caused remarkable erosion of the southern end of the spit, where coastal retreat amounts to 560 m in the period 1976-2000 (MARTÍNEZ-DEL-POZO *et al*., 2001). As a consequence of this, more than one million square meters of beach, dunes and salt marshes have been lost in the last 25 years. Although coastal retreat in this area develops as a rollover process so the whole system moves back, active erosion processes prevent the formation of embryo dunes, and the few existing foredunes are very low and narrow (Fig. 6).

Despite the loss of many dune fields and the damage in most remaining dune areas, there are still several well-preserved dune systems in the northern coast of the province such as El Chato and Castilnovo beaches (Fig. 1). In other places the dune state has been improved by interventions of the Ministry of the Environment, for example at northern El Palmar beach. Here the revegetation of the dunes, together with the installation of palissades and protective fences, have stabilized the dune area to a great extent, leading to a dunefoot advance of up to 20 m at some points in the last 25 years.

Southern coast

The southern part of the study area is located between Cape Trafalgar and Tarifa. Here the proximity to the Strait of Gibraltar and the narrowing of the continental shelf produce a sharp reduction in tidal range. The coast is mainly composed of small embayments fed by short rivers with little sedimentary load, and pocket beaches between headlands, relatively sheltered from westerly storms. Beaches are generally narrower and steeper than in the northern coast, showing intermediate to reflective profiles.

As a consequence of these conditions, shore-parallel dune ridges are less well developed than in the north of the province. On the other hand, coastal morphology and the strength of easterly (*Levante*) shore-parallel winds in this area are responsible for the extensive development of high, non-vegetated, climbing dunes in the shadow of headlands, with associated barchanoid morphologies. Most of these dunes have grown rapidly due to human interventions as discussed below.

One of the most spectacular cases is that of Bolonia embayment, where a 1500 m long deflation corridor related to *Levante* wind used to connect Bolonia and El Cañuelo beaches (Fig. 1). After extensive planting of pine trees along the deflation corridor in the middle 1950s to prevent sand from burying a road, the vertical growth of Bolonia dune under the influence of *Levante* winds quickly reached 30 m high. Today the non-vegetated Bolonia dune and barchans cover an area of about 92,000 m^2 (Fig. 7), and the dune front is moving forward and burying pine trees at an average rate of 2 m/year. However, as the road is not endangered anymore, very few further stabilization measures have been applied to the dune, which is a protected area.

A similar human-induced growth process affected Valdevaqueros dune after pines and eucalyptus trees were planted between the 1930s and 60s in the massive Betis aeolian mantle, a deflation corridor that extended 5500 m from Valdevaqueros embayment (Fig. 1), in order to prevent the burial of a road located right behind the dune. More recent attempts at dune stabilization, including the periodic removal of sand and the placing of palisades, have resulted in the growth and widening of the non-vegetated dune area, which now covers around 152,000 m^2. Despite the control measures, the dune front is more than 30 m high (Fig. 8) and has advanced around 120 m during the last 25 years, and dune sand still threatens the road.

At several points along the coast, local topography has led to the formation of narrow shore-parallel dune ridges. At Los Lances beach (Fig. 1), the mouth of Jara stream modifies the beach shape and supplied sand to the system, and as a result a continuous shore-parallel dune system with embryo dunes and foredunes extends for almost 2 km along the beach.

A particular case is that of Hierbabuena beach (Barbate village, Fig. 1), where the blocking of longshore drift by Barbate harbour together with the revegetation of dunes by the Ministry of the Environment has remarkably increased the beach and dune surface. In 1956 Hierbabuena beach covered an area of about 47,000 m^2 and no significant dunes were present; four decades later, the total area covered by beach/dune systems is around 192,000 m^2, most of it (nearly 110,000 m^2) occupied by a well-developed dune field.

The overall good preservation of dune areas in the southern province is mainly due to the relatively low human occupation of the coast, as a great part of it belongs to the Ministry of Defence or is environmentally protected, and urban development is therefore not allowed or very restricted. In fact, many dune areas

Figure 6. Eroded foredunes at Valdelagrana beach.

Figure 7. Climbing dune at Bolonia Bay.

Figure 8. Control measures (above) and mobile front (below) in Valdevaqueros dune.

were destroyed before the approval of Spanish Shores Act in the few places where building was not restricted, like Caños de Meca beach, where nearly 50,000 m^2 of dunes were removed for building purposes in the 1960s and early 70s. Recent significant coastal development in some places, like Atlanterra beach, is located behind the dune areas, as required by the Shores Act.

Another important factor contributing to dune preservation is the practical absence of coastal erosion in the southern part of the province, where most beaches are not dependent on fluvial sediment supply and coastal setting is responsible for the limited importance of westerly erosive waves (DEL RÍO *et al.*, 2005). However, there are some local exceptions like Caños de Meca beach, where a shoreline retreat between 25 and 75 m in the last 50 years has caused the disappearance of embryo dunes.

DISCUSSION AND CONCLUSIONS

Climatic changes, even the slight ones that have occurred in historical times, affect the location of the main low and high pressure systems in the North Atlantic, and hence very probably control the direction and intensity of winds in the Gulf of Cádiz. In addition, historical climatic fluctuations also influenced vegetation cover, sediment production on river watersheds and stability of beaches and littoral spits. Climatic curves deduced from pollen analysis in the Bay of Cádiz (LÓPEZ *et al.*, 2002) match reasonably well with palaeoclimatic models derived from different sources in western Europe (VIGNES *et al*., 2002). In the last 2000 years palaeoclimatic records in the zone suggest only slight thermal oscillations, although some of them may have been misinterpreted due to human influence (REED *et al*., 2001).

It is reasonable to suppose that the historical fluctuations of the NAO mainly controlled the prevalence of easterly or westerly winds (and probably waves) during different periods. Positive oscillations of the NAO index very probably favored the growth and extension of mobile dunes along all the bays of this coast.

In the historical records most of these episodes may appear as aeolian deposits of variable thickness, associated with a higher frequency and persistence of easterly (*Levante*) winds. The reconstruction of prevailing wind direction responsible for the generation of the deposits can be deduced from the geometry of the sand body or from laminae dipping in dune deposits. However, in certain cases local contouring conditions (such as those that occur in embayments) produce deviations in the main wind direction, which can lead to misinterpretations.

During the 20th century, and especially during the last few decades, positive values of the NAO index have prevailed in the South of the Iberian Peninsula. As a consequence, *Levante* winds have favored the growth and advance of mobile dunes in the vicinity of the Strait of Gibraltar, locally enhanced by human interventions. In contrast, dune ridges associated with westerly more humid *Poniente* winds are much less mobile or stable and usually form simple systems with two or three shore-parallel ridges, mostly covered by vegetation.

The present state of dune systems in the Cadiz coast (Fig. 9) is strongly dependent on the prograding/retreating trend of the adjacent beaches, since in most cases they constitute the main aeolian sediment source. Most of the beach sediments are supplied by the main rivers discharging to this coast: Guadalquivir, Guadalete and, to a much lesser extent, Salado and Barbate. The two former rivers are highly regulated by dams and the associated decrease of sediment output during the last decades has produced a continued retreating trend in the beaches surrounding their mouths, especially those located downdrift (Sanlúcar – Chipiona – Rota, Valdelagrana, Sancti Petri and La Barrosa; see Fig. 1). The recent damming of the Barbate River is producing similar consequences southwards of Barbate village. At the same time, the northern sector presents a relatively high density of coastal settlements, where increasing urbanization has led to the destruction and occupation of dunes ridges. In summary, between Sanlúcar-de-Barrameda and Chiclana coastal dunes are severely degraded and in many cases completely destroyed.

Figure 9. Present state of dune systems in the Atlantic coast of Cadiz province.

ACKNOWLEDGEMENTS

This is a contribution to DIVULGA Research Project (BTE2003-05706, supported by the Spanish Ministry of Science & Technology and by European ERDF) and to the Andalusian PAI Research Group RNM- 328. This is also a contribution to IGCP Project 437.

LITERATURE CITED

ABERG, U., 2005. *Recent berm ridge development inside a mesotidal estuary: The Guadalquivir River mouth case.* Uppsala, Sweden: University of Uppsala, Undergraduate thesis, 62p.

ALONSO, C.; GRACIA, F.J. and BENAVENTE, J., 2004. Las marismas, alfares y salinas como indicadores para la restitución paleotopográfica de la Bahía de Cádiz durante la antigüedad. *In: XVI Encuentros de Historia y Arqueología.* San Fernando, Spain: Ayuntamiento de San Fernando, pp. 263 – 287.

BENAVENTE, J.; DEL RÍO, L.; ANFUSO, G.; GRACIA, F.J. and REYES, J.L., 2002. Utility of morphodynamic characterization in the prediction of beach damage by storms. In: COOPER, J.A.G. and JACKSON, D.W.T. (eds.), *International Coastal Symposium*. Journal of Coastal Research Special Issue No. 36, pp. 56 - 64.

BIRD, E.C.F. and JONES, D.J.B. 1988. The origin of foredunes on the coast of Victoria, Australia. *Journal of Coastal Research*, 4, 181 –192.

BORJA, F., 1992. *Cuaternario reciente, Holoceno y periodos históricos del SW de Andalucía. Paleogeografía de medios litorales y fluvio-litorales en los últimos 30.000 años.* Seville, Spain: University of Seville, Ph.D. thesis, 520p.

BORJA, F.; ZAZO, C.; DABRIO, C.J.; DIAZ DEL OLMO, F.; GOY, J.L. and LARIO, J., 1999. Holocene aeolian phases and human settlements along the Atlantic coast of southern Spain. *The Holocene*, 9 (3), 333 - 339.

CARTER, R.W.G., 1988. *Coastal environments*, 3rd ed. New York: Academic Press, 617 p.

DABRIO, C.J.; ZAZO, C.; LARIO, J.; GOY, J.L., SIERRO, F.J.; BORJA, F.; GONZÁLEZ, J.A. and FLORES, J.A., 1999. Sequence stratigraphy of Holocene incised-valley fills and coastal evolution in the Gulf of Cádiz (southern Spain). *Géologie en Mijnbouw*, 77, 263 – 281.

DABRIO, C.J.; ZAZO, C.; GOY, J.L.; SIERRO, F.J.; BORJA, F.; LARIO, J.; GONZÁLEZ, J.A. and FLORES, J.A., 2000. Depositional history of estuarine infill during the last postglacial transgression (Gulf of Cadiz, Southern Spain). *Marine Geology*, 162, 381 - 404.

DEL RÍO, L.; GRACIA, F.J.; BENAVENTE, J. and ANFUSO, G., 2005. Alongshore variations in coastal erosion in the Atlantic side of Gibraltar Strait (SW Spain): causes and consequences. *Abstract Volume of the 6th Intern. Conference on Geomorphology*, (Zaragoza, Spain), pp. 247.

DOMÍNGUEZ, L.; GRACIA, F.J. and ANFUSO, G., 2004. Tasas de avance-retroceso de la línea de costa mediante morfometría fotogramétrica en el sector Sanlúcar de Barrameda-Rota (provincia de Cádiz). *Revista de la Sociedad Geológica de España*, 17(1-2), 71-86.

GOODESS, C.M. and JONES, P.D., 2002. Links between circulation and changes in the characteristics of Iberian rainfall. *International Journal of Climatology*, 22, 1593 – 1615.

GOY, J.L.; ZAZO, C.; DABRIO, C.J.; LARIO, J.; BORJA, F.; SIERRO, F.J. and FLORES, J.A., 1996. Global and regional factors controlling changes of coastlines in southern Iberia (Spain) during the Holocene. *Quaternary Science Reviews*, 15, 773 – 780.

GOY, J.L.; ZAZO, C. and DABRIO, C.J., 2003. A beach-ridge progradation complex reflecting periodical sea-level and climate variability during the Holocene (Gulf of Almería, Western Mediterranean). *In*: MATHER, A.E. and STOKES, M. (eds.), *Long-term landscape development in Southern Spain*. Geomorphology, 50(1-3), 251 – 268.

GRACIA, F.J.; ALONSO, C.; BENAVENTE, J. and LÓPEZ AGUAYO, F., 2000. Evolución histórica de la línea de costa en la Bahía de Cádiz. *In*: DE-ANDRÉS, J.R. and GRACIA, F.J. (eds.), *Geomorfología Litoral. Procesos activos*. Cádiz, Spain: University of Cádiz Press, pp. 225 - 234.

GRACIA, F.J.; BENAVENTE, J. and MARTÍNEZ DEL POZO, J.A., 2002. Geomorfología y emplazamiento. Enmarque holoceno de “El Retamar”. *In*: RAMOS, J. and LAZARICH, M. (eds.), *El asentamiento de "El Retamar" (Puerto Real, Cádiz).* Cádiz, Spain: University of Cádiz Press, pp. 27 - 36.

HURRELL, J.W., 1995. Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation. *Science*, 269, 676 – 679.

JENNINGS, J.N. (1964) The question of coastal dunes in tropical humid climates. *Zeitschrift für Geomorphologie*, 8, 150 – 154.

LÓPEZ, J. A.; LÓPEZ, P. and MARTÍN, M., 2002. Paleoecology and Holocene environmental change fron a saline lake in South-West Spain: protohistorical and prehistorical vegetation in Cádiz Bay. *Quaternary International*, 93-94, 197-206.

MARTÍNEZ DEL POZO, J.A.; ANFUSO, G. and GRACIA, F.J., 2001. Recent evolution of a tidal delta in Cádiz Bay (SW Spain) due to human interventions. *In*: OZHAN, E. (ed.), *Proceedings 5th International Conference on Mediterranean Coastal Environment, MEDCOAST'01*. Hammamet, Túnez: pp. 1425 - 1433.

MUÑOZ-PÉREZ, J.L. and SÁNCHEZ, A., 1994. *El medio físico y biológico en la Bahía de Cádiz: Saco Interior.* Seville, Spain: Conserjería de Agricultura y Pesca, Junta de Andalucía, 161p.

REED, J.M.; STEVENSON, A.C. and JUGGINS, S. (2001). A mulit-proxy record of Holocene climatic change in southwestern Spain: the Laguna de Medina, Cádiz. *The Holocene*, 11(6), 707 – 719.

RODRIGO, F.S.; ESTEBAN, M.J., POZO, D. and CASTRO, Y. 1999. A 500-year precipitation record in Southern Spain. *International Journal of Climatology*, 19, 1233 – 1253.

SÁNCHEZ, J.L., 1988. *Estudio climatológico de la Bahía de Cádiz. Instituto Hidrográfico de la Marina*. Cádiz, Spain: Ministerio de Defensa, 150p.

STIPP, J.J. and TIMERS, M.A., 2002. Datación radiométrica. *In*: RAMOS, J. and LAZARICH, M. (eds.), *El asentamiento de "El Retamar" (Puerto Real, Cádiz). Contribución al estudio de la formación social tribal y a los inicios de la economía de producción en la Bahía de Cádiz.* Cádiz, Spain: University of Cádiz Press, pp. 169 – 172.

TRIGO, R.M.; POZO, D.; OSBORN, T.J.; CASTRO, Y.; GÁMIZ, S. and ESTEBAN, M.J., 2004. North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *International Journal of Climatology*, 24, 925 – 944.

VIGNES, J. D.; BAILON, S.; CUISIN, J. and DESSE-BERSET, N., 2002. Sensibilité des microvertébrés aix fluctuations hygrométriques tardiglaciaires et holocènes: deux séquences en zone méditerranéenne humide (Grítulu et Monte di Tuda, Haute-Corse). *In*: BRAVARD, J.P. and MAGNY, M. (eds.), *Les fleuves ont une histoire. Paléo-environnement des rivières et des lancs français depuis 15.000 ans.* Paris, France: Éditions Errances.

ZAZO, C.; GOY, J.L.; SOMOZA, L.; DABRIO, C.J., BELLUOMINI, G.; IMPROTA, S.; LARIO, J.; BARDAJÍ, T. and SILVA, P.G., 1994. Holocene sequence of sea-level fluctuations in relation to climatic trends in the Atlantic-Mediterranean linkage coast. *Journal Coastal Research*, 10, 933-945.

View publication stats